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1. The first part of the program is the title page.

2. The second part is the introduction.

3. The third part is the main body of the program.

4. The fourth part is the conclusion.

5. The fifth part is the bibliography.

6. The sixth part is the appendix.

7. The seventh part is the index.



# THE AUTO AND CROSS-CORRELATION PROGRAM FOR THE LAB-8

DECUS Program Library Write-up

DECUS NO. 8-340

## INTRODUCTION

A variety of techniques are available for extracting signals from their noisy environments. These include filtering (frequency domain), signal averaging (amplitude domain), and correlation (time domain). Each technique has its own advantages and disadvantages and hence its own area of application.

Correlation, as it applies to waveforms, can be used to detect periodic signals buried in noise or provide a measure of similarity between two waveforms. Autocorrelation measures the similarity of a signal to a time delayed version of itself, while cross-correlation measures the degree of similarity of one source or input to a second source. No synchronizing events, such as the trigger required in signal averaging, need be available for the application of correlation techniques.

Typical applications for correlation include:

- 1) Determination of the transmission paths and propagation velocities of mechanical vibrations, acoustic, and seismic waves.
- 2) Indication of epilepsy through comparison of electroencephalograms from the two halves of the brain.
- 3) Measurement of impulse-response characteristics of servo control systems in the presence of noise.
- 4) Analysis of the tremor frequencies of patients afflicted with Parkinson's disease.
- 5) Detection of very weak and distant radio sources in space.
- 6) Speech research in telecommunications, education for the deaf, and non-computer interfaces.

## THEORY

Mathematically, the autocorrelation function is defined as:

$$R_{xx}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t)x(t-\tau) dt \quad (1)$$



where  $x(t)$ , the time function of interest is multiplied by a time delayed version of itself  $x(t-\tau)$ , and the product of the two values averaged over the observation time  $T$ . The resulting average approaches an exact correlation as  $T$  approaches infinity.

Cross-correlation is very similar to autocorrelation, the difference being that the input is multiplied by a time delayed version of a second signal, rather than a time delayed version of itself. The cross-correlation function of a waveform is defined as:

$$R_{xy}(\tau) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x(t) y(t-\tau) dt \quad (2)$$

To apply digital computing techniques to the above equations, it is convenient to approximate the average by sampling the signal at regular intervals, say  $t$ , and then summing a finite number,  $k$ , of the sample products. Rewritten in discrete form, equation (1) becomes:

$$R_{xx}(\tau) \approx \frac{1}{k+1} \sum_{i=0}^k x(t_i) x(t_i - \tau) \quad (3)$$

If the maximum time delay  $\tau_{\max}$  is divided into  $N$  intervals of  $\Delta\tau$  each and the time between samples  $\Delta t$  is made equal to the time delay increment  $\Delta\tau$  equation (3) becomes:

$$R_{xx}(n\Delta\tau) \approx \frac{1}{k+1} \sum_{i=0}^k x(t_i) x(t_i - n\Delta\tau) \quad \text{where: } n=0, 1, 2, 3, \dots, N \quad (4)$$

which is the equation used in the LAB-8 program. Similarly, equation (2) can be approximated by:

$$R_{xy}(n\Delta\tau) \approx \frac{1}{k+1} \sum_{i=0}^k x(t_i) y(t_i - n\Delta\tau) \quad (5)$$

## PROPERTIES AND EXAMPLE OR CORRELATION

The autocorrelation function can be shown to have the following properties:

- 1) Autocorrelation is an even function; i.e.,  $R_{xx}(\tau) = R_{xx}(-\tau)$ , therefore, the correlogram need only be computed and displayed for positive values of  $\tau$ .  $\tau = 0$  is displayed at the left of the screen.
- 2) The autocorrelation function has its maximum value for  $\tau = 0$ . Sometimes it is convenient to set this value corresponding to  $\tau = 0$  to 1 and express all other data as a fraction. The CNTRL/T command of the program does this automatically.



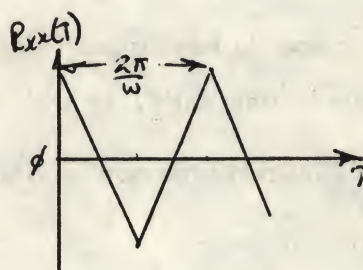
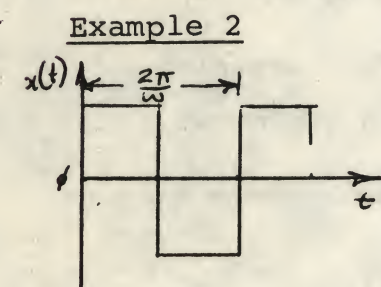
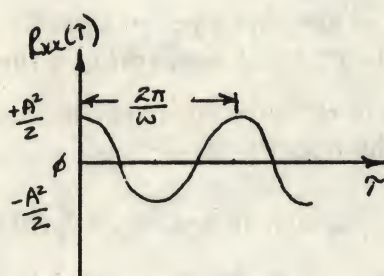
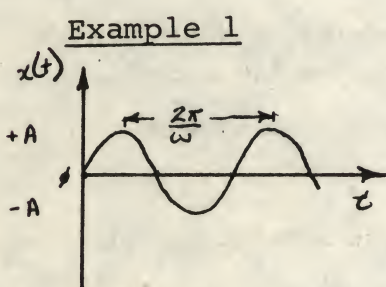
3) The value of the autocorrelated function for  $\tau=0$  is the mean square voltage of the time function, substituting  $\tau=0$  in equation (1).

$$R_{xx}(\phi) = \lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T x^2(t) dt = x^2(t)$$

The T command in the program automatically normalizes the data and types it out as  $m \tau^2$ .

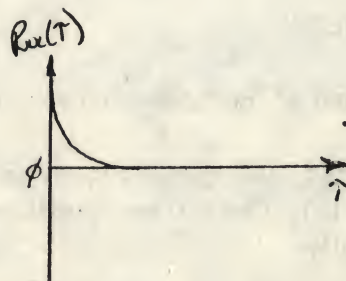
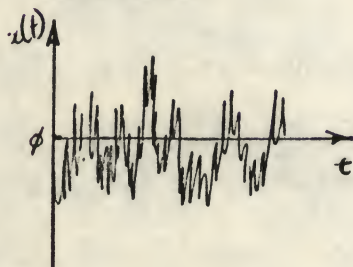
4) If the time function contains periodic components, the autocorrelation function will contain components having the same periods.

### Example 1



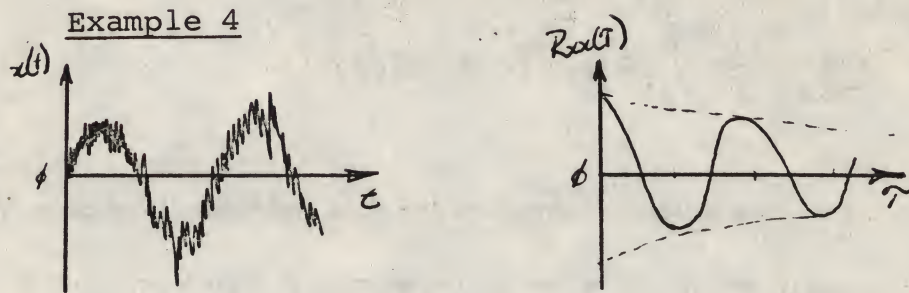
5) If the function contains only random components (noise) and no periodic components, the autocorrelation function will approach zero as  $\tau$  increases. The rate at which it approaches zero is a measure of the randomness of the time function and, therefore, the bandwidth of the noise.

### Example 3





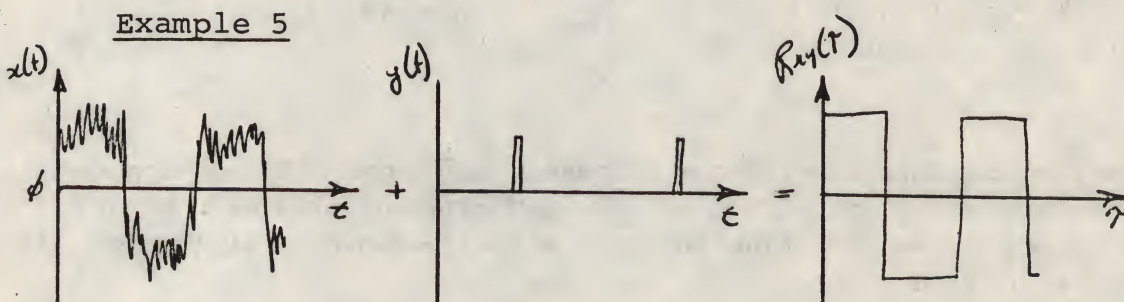
6) If the time function is composed of two or more components, the resultant autocorrelation function will be the sum of the autocorrelation functions of each individual component.



The cross-correlation function can be shown to have the following properties:

- 1) The cross-correlation function is not necessarily an even function, and therefore, in general  $R_{xy}(\tau) \neq R_{xy}(-\tau)$ . Consequently, a time shift of one input function in one direction with respect to the other does not produce the same result as an equal shift of the same function in the opposite direction.
- 2)  $R_{xy}(\tau) = R_{yx}(-\tau)$ . A shift in one input function  $x(t)$  in one direction must yield the same result as an equal shift of the other input function  $y(t)$  in the opposite direction.
- 3)  $R_{xy}(\tau)$  does not necessarily have a maximum at  $\tau = 0$ . The maximum value of  $R_{xy}(\tau)$  will occur for that value of time shift  $\tau$  for which the two input functions are most alike.

The following example illustrates the application of the cross-correlation function:



## PRINCIPLE OF OPERATION

A simplified block diagram of the LAB-8 correlation program is shown in Figure 1.

When the program is started, the user is requested to reply to three questions: rate, number of points, and auto? Once these questions have been answered, the program does the following automatically:



- 1) Sets the clock to take analog samples at the specified rate. Sampling rate =  $\Delta T$ .
- 2) Sets up a single precision buffer to hold the delayed samples.
- 3) Set up a double precision buffer to hold the correlogram data.
- 4) Sets the software auto/cross switch to the proper position.

The data collecting part of the program may now begin.

The memory updating process can be visualized as continually storing data in a closed loop. After each revolution of the loop, the oldest data point in the shift register is replaced by a new sample.

As each sample is converted into an equivalent digital value by the analog-to-digital converter it is stored in the single precision store. This buffer acts in a manner similar to a shift register. That is, for each new sample entered, the oldest sample is lost.

As the data is being shifted along in the single precision store, calculations are being carried out to update the correlogram. Each data point is multiplied by the most recent sample ( $T=0$ ) and the product is added to the corresponding cell in the double precision store. In cross-correlation, the multiplier is a sample from another channel. Table 1 shows the calculations formed for cross-correlation.

<u>Samples</u>		<u>Shift Register Number</u>			
<u><math>t_i</math></u>	<u>0</u>	<u>1</u>	<u>2 . . . . . n</u>		
$t_0$	$x(t_0)y(t_0)$	$x(t_0)y(t_0-\Delta T)$	$x(t_0)y(t_0-2\Delta T) \dots x(t_0)y(t_0-n\Delta T)$		
$t_1$	$x(t_1)y(t_1)$	$x(t_1)y(t_1-\Delta T)$	$x(t_1)y(t_1-2\Delta T) \dots x(t_1)y(t_1-n\Delta T)$		
$t_2$	$x(t_2)y(t_2)$	$x(t_2)y(t_2-\Delta T)$	$x(t_2)y(t_2-2\Delta T) \dots x(t_2)y(t_2-n\Delta T)$		
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
$t_i$	$x(t_i)y(t_i)$	$x(t_i)y(t_i-\Delta T)$	$x(t_i)y(t_i-2\Delta T) \dots x(t_i)y(t_i-n\Delta T)$		
	$\sum_{i=0}^k x(t_i)y(t_i)$	$\sum_{i=0}^k x(t_i)y(t_i-\Delta T)$	$\sum_{i=0}^k x(t_i)y(t_i-2\Delta T)$	$\sum_{i=0}^k x(t_i)y(t_i-n\Delta T)$	

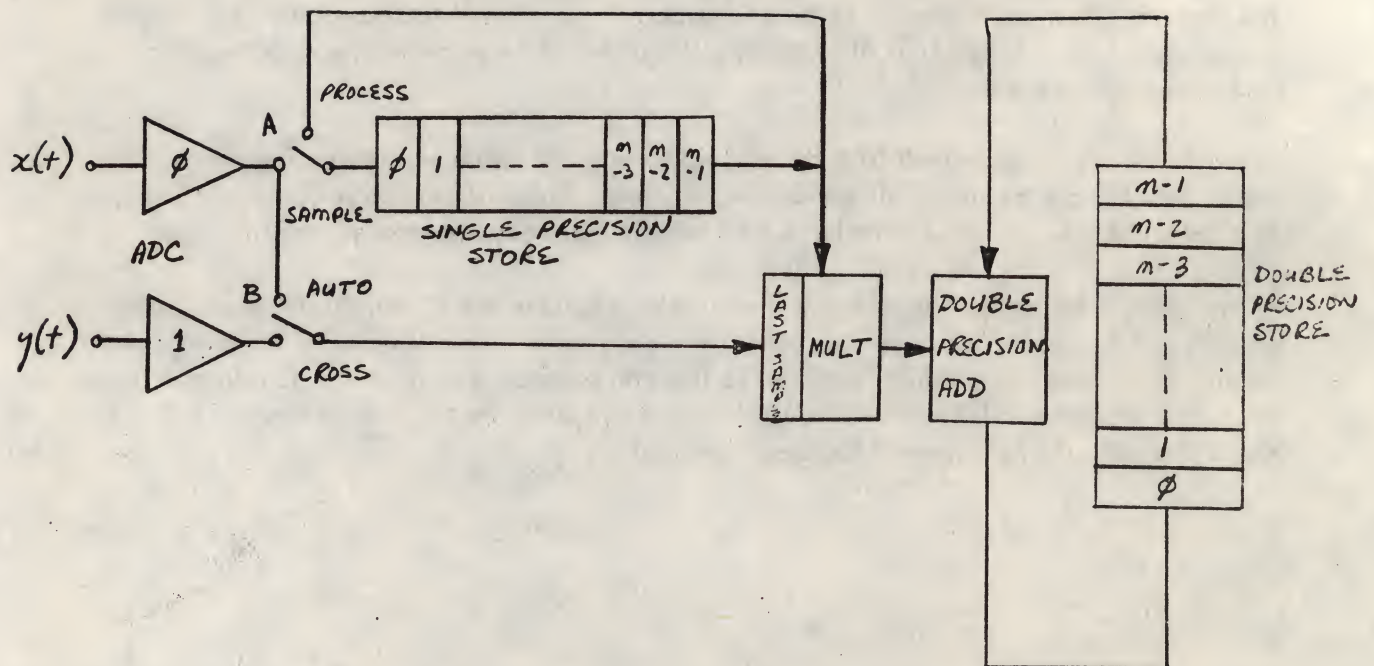


FIGURE 1 SIMPLIFIED BLOCK DIAGRAM OF THE LAB-8 CORRELATION PROGRAM



## ABSTRACT

The LAB-8 Auto and Cross-Correlation Package is designed to correlate data at sampling rates ranging from .1 to 204.7 milliseconds, on line, with the user controlling all parameters from the Teletype. It displays and scales data while computing, and provides output that can be used with FOCAL or users programs.

The Auto and Cross-Correlation Package comes in two versions: EAE and NON-EAE. The EAE package correlates 7 bit samples (6 bits + sign) while the NON-EAE correlates 5 bit samples (4 bits + sign). The only external difference between the two packages is that the EAE correlagram has better resolution than the NON-EAE version.

## REQUIREMENTS

- PDP-8/I or 8/L with DW08A I/O Conversion Panel
- AX08 Laboratory Peripheral
- RM503 Oscilloscope
- LAB-8 PST Histogram Program
- High Speed Reader/Punch is used when available

## LOADING

The binary tape of either version is loaded using the binary loader. First, place the tape in the ~~high or low speed~~ reader, and advance to leader/trailer. Then put 7777 in the switch register, depress LOAD ADD. If loading with the high speed reader, set bit 0 to 0. Depress START.

After the tape has been loaded, place 0200 in the SR, depress LOAD ADD, and push START.

The binary tape can be loaded with the disk monitor system by following the disk monitor's instructions for loading tapes. (i.e., SAVE! AUTO!)

## USING THE AUTO & CROSS-CORRELATION PACKAGE

LOAD the binary tape as described in section on LOADING.

Once the program has been started, it types: (Through the remainder of this document, all computer generated output will be underlined.)

RATE: The user then types in the sampling rate (t) in milliseconds. The number typed in must be in one of four formats:

- 1) XXX.X
- 2) XX.X
- 3) X.X

"X" signifies a decimal digit. The value of the number typed in must be in the range of



.1 to 204.7. If the number exceeds this range, then the user is notified of his mistake by the following message:  $000.0 < \text{RATE} < 204.8$ . In practice the rate specified should always be at least 4x the maximum frequency being sampled.

If the user types something that is not a digit, then it is ignored and not echoed.

The sampling rate is the time between the taking of samples from the analog to digital converter.

Once the rate has been input, the computer types:

NO. OF POINTS: This parameter defines the number of points that will make up the correlogram. Input is a decimal number of no more than three digits. Its range is: 4 number 513. If the number entered is outside of this range, the following message is typed to inform the user of his mistakes:  $4 < \# \text{ OF POINTS} < 513$ .

In all cases, when typing a number to define the rate and number of points, input can be restarted by typing a rubout, which echoes a back slash ( \ ). Input can be prematurely terminated when typing the number of points by hitting the carriage return.

Once the number of points and sampling rates have been defined, the computer types: AUTO?

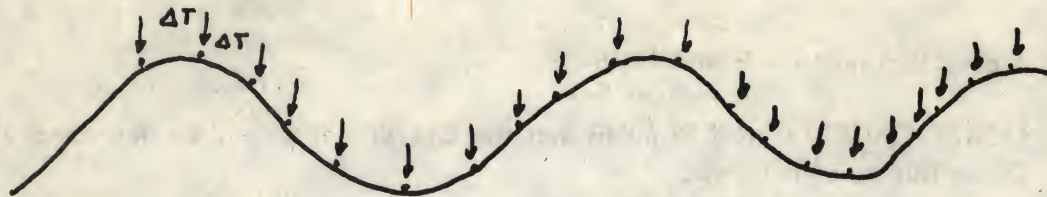
If the user intends to Auto correlate a signal, then he responds with a "Y"; if he intends to Cross-correlate, then he types a "N". Any other characters are ignored and not echoed.

After the user has typed his reply, the program types either BATCH MODE, or NORMAL MODE.

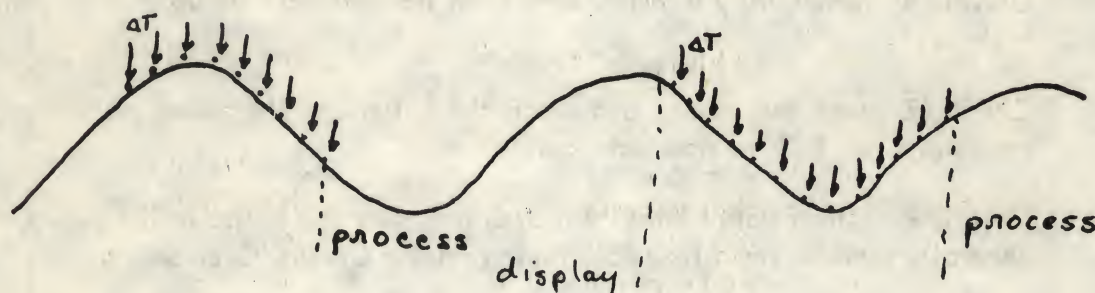
A small regression is necessary to explain the difference between BATCH and NORMAL MODE. It was found that to process one point took at least 200  $\mu$  secs. To process N points took at least (200XN)  $\mu$ secs. Thus the user, when defining the rate and number of points, had to make sure he was allocating at least 200  $\mu$ secs per point. For example, suppose one defined the rate as 20.0 milliseconds., and the number of points as 100. 20.0

milliseconds. = 20,000 microsecs.,  $\frac{20,000}{100} = 200 \mu\text{secs. per point}$ . But what if the rate were 20.0 msec., but with 200 points; this would mean 100  $\mu$ secs. per point; which is not enough time to process one point. When there are 200 or more microseconds per point, the correlator operates in NORMAL MODE, that is, it does one entire sweep, reads in a new value from the ADC, does another sweep, etc. This provides a steady sampling rate. However, if the time allocated to the processing of one point is less than 200  $\mu$ secs., then BATCH MODE is entered. In this mode, the entire buffer is filled with samples taken at the defined rate. Once N+1 samples have been taken, the buffer is multiplied by the last sample and displayed, after which new data is taken. The following graphs illustrate the two modes:





The arrows represent the places on the graph where samples are taken. It is the time between samples, or the rate. During this time, the buffer is processed.



Because of its nature, BATCH MODE takes longer to yield a clean correlogram. Therefore the user should operate in NORMAL MODE whenever possible.

After the computer notifies the user of the mode, it displays the empty buffer and waits for CNTRL/S to start data collection.

NOTE: During the time of parameter setup, one can type CNTRL/A to restart the parameter setup routine, or a CNTRL/C to jump to 7600 and return to monitor, if it exists.

### Input Connections

If doing autocorrelation, the lead must be connected to channel 0. If cross-correlation, the 2 leads must be connected to channels 0 and 1. The shift register is filled with samples from channel 0. In either case the input should be externally adjusted to in the range of  $\pm 1.0$  volt. For best results the input should be as close as possible to  $\pm 1.0$  volt.

### Commands

There are two major groups of commands:

GROUP I: These commands are active during data collection.

GROUP II: These commands cannot interrupt data, collection and are ignored if typed while data is being correlated.



A description of commands follows:

NOTE: CNTRL/X or  $\uparrow$  X mean that the CNTRL key should be depressed while the letter (X in this case) is typed.

#### Group I Commands:

CNTRL/S starts data taking. It clears the buffer and all counters before starting.

CNTRL/C stops data collection, turns off the clock, and jumps to 7600 in field 0. If running with the disk monitor system, this will return control to the monitor.

CNTRL/A immediately transfers control of the parameter setup routines, and clears the buffers.

CNTRL/Z stops data taking and clears the buffer and the sweep counter. The program then waits for  $\uparrow$  S to start data collection.

CNTRL/R restarts data taking, but does not clear the buffer or the sweep counter. It is generally used for restarting data taking after a CNTRL/Q command.

CNTRL/Q stops data collection after the current sweep and enables all Group II commands.

CNTRL/U is an unimplemented user command. Details of its implementation may be found in a listing (available through the program library, DEC, Maynard, Mass.)

U expands the display of the correlogram by a factor of 2. The scale factor is initially set to 1 in the EAE version and to two to the fourth power in the non EAE version.

D contracts the display of the correlogram by a factor of 2. Display of input is not affected.

V determines whether the input or the correlogram is displayed. The input is initially displayed. Typing "V" will switch the display from input to correlogram, or vice versa. When switching modes, the display soon deteriorates due to interrupts in the middle of the display loop.

X effects only the display of the correlogram. The base line is shifted by the value of Knob 2. The base line will be biased by the same amount each time "X" is typed. The correlogram can thus be moved up and down on the scope.

Z restores the correlogram to its unbiased X axis. It is used to counteract all previous X commands.

#### GROUP II COMMANDS

When  $\uparrow$  Q is typed, the program transfers to the output mode. During the output mode both Group II and Group I commands are active.



C alternately turns on and turns off the display of cursors. The cursors are initially off. Two cursors are displayed. Their location on the X-axis are determined by knobs 0 and 1. The location of the cursors can thus be determined by the knobs.

N types out the number of sweeps and the current scale factor in the following format:

XXXXXXX (# of sweeps)

2 ±XXXXXXX (Scale Factor)

where X is a decimal digit. The number of sweeps is defined as the number of times the first position of the shift register is multiplied by the results of an A/D sample.

K calibrate an x-y analog plotter. When the K command is given, the outputs of the oscilloscope go to zero volts for the horizontal and zero volts for the vertical. When any non command key on the keyboard is struck, the outputs each go to -10 volts. By striking any other key, the outputs will go back to zero volts. This process may be repeated as many times as needed while the bias and gain controls for the x-y plotter are adjusted. (See the appendix for details of attaching an analog recorder.) When the plotter is calibrated, ↑ Q should be typed and the display will be resumed.

P is used to plot the displayed waveform on an analog plotter. After "P" is typed, the first point is displayed, and the plot routine waits for a character to be typed before proceeding with the plot. The plotter should now be turned on. Once a character has been typed, the data is plotted. The speed of the plot is determined by the range and fine "Timing Controls" on the AX08.

These should be adjusted until the plotting speed is appropriate for the plotter being used. For a first approximation, turn the range knob fully counterclockwise, then turn it clockwise three positions. At the end of the plot, the routine stops, waiting for a character to be typed before proceeding. This is to allow the user time to turn off the plotter. After the character is typed, plot mode is terminated, and the display returns to normal.

CNTRL/O is an unimplemented user command. For details of implementation see a listing (available through program library, DEC, Maynard, Mass).

CNTRL/B causes a binary dump of the correlogram. Note: The correlogram will be returned to normal size and scale before the binary dump takes place. After the initial command of " ↑ B" the computer will type OUT? The user should answer "H" if the dump is to proceed on a high speed punch or "L" if the teletype punch is to be used. (Any non command character is ignored and not echoed.) After this initial question the computer will type NAME: Here the user may enter a maximum of 6 characters followed by a carriage return for an identification code. Caution: - the following characters may not be used in the ID code. Rubout, ↑ C, or ↑ A. The pressing of the Rubout key will cause input to be zeroed and then restarted.



After the ID code has been entered leader/trailer punches will be punched. If the low speed punch is to be used, it should be turned on during the leader/trailer. Following the leader/trailer code, the ID code will be punched in ASCII and will be followed by more leader/trailer punches.

After the identifying information has been output, a core image of the correlogram and a checksum will be punched. A core image dump allows the paper tape to be read back into the computer in the same form as it was originally dumped. The binary loader can be used to reload the data. This feature allows the user to take data, dump it and then return at any later time to process or review it. The user may write his own processing program or he can read the data back into the auto and cross-correlation program. For details of binary format see the Appendix. To review the data with the auto and cross-correlation program, load the program as described in section on LOADING (if the program is in core, give the command ↑ Z; reloading is not necessary).

After the program is in core, load the data with the binary loader. After the data and programs are in core, start the program at location 7560 (place 7560 in the front switches, press load address, and start). Now operate the program as if the output mode had just been entered.

NOTE 1: Since only the correlogram is dumped and not the temporary buffer, reloading of the data may cause a bad display of the temporary buffer. This will not effect the proper operation of the program.

NOTE 2: If this program is run from disk or DEctape, the correlogram can be dumped by the following procedure.

- 1) Hit ↑ C - monitor returns.
- 2) Save page zero and locations 3200-6177 as binary files.
- 3) Restart the programs at location 7560.
- 4) Continue as if a binary dump had taken place.

To review this data, load the auto and cross-correlation program, then the data. Start at location 7560.

After the Binary dump has taken place the program returns to the active display and all of the commands are operative.

T Types out the data between the cursors. If the Cursors overlap one another, the typeout routine is immediately exited. An example of the output follows:

<u>0000001</u>	<u>0000004</u>	<u>0000804</u>	<u>0000004</u>	<u>0000200</u>
<u>0175872</u>				
<u>0057856</u>				
<u>0035072</u>				
<u>-0015872</u>				



On the first line the first number (00000001) signifies that the left most cursor is on the first point of the correlogram. 00000004 is the position of the right most cursor (i.e., the fourth point of the correlogram). 00008004 is the sweep count. The sweep count indicates the number of times the first position of the shift register was multiplied by an ADC sample. 00000004 is the number of points whose values are being typed out and 00002000 indicates that  $200 \times 100 \mu\text{sec}$  or 20 msec is the amount of time represented by the distance between the cursors.

Line two: 0175872 is the normalized value for the first position of the correlogram.

Line three: 0057856 is the normalized value for the second position of the correlogram.

Etc.

Before the data is typed, it is normalized by one of the following standard equations:

For "normal mode" normalization:

$$\text{Normalized value of the } i\text{th point} = \frac{(\text{raw value of the } i\text{th point})}{(\text{number of sweeps}) - (i)}$$

For "batch mode" normalization:

$$\text{Normalized value of the } i\text{th point} = \frac{(\text{Raw value of the } i\text{th point})}{(\text{number of sweeps})}$$

The units for the data points are (millivolts)<sup>2</sup>

Typeout will continue until all of the data between the cursors has been output. Typeout may be stopped prematurely by the "↑ Q" command.

CNTRL/T This command is similar to the "T" command in that it also types out the data. The first line of output will be identical to the first line of typeout obtained from the "T" command. However, the data points are typed out as correlation coefficients, ranging from +1 to -1, rather than as normalized values.

NOTE: This command should only be used while doing autocorrelation. The results are meaningless for cross-correlation.

An example of the output follows:

<u>00000001</u>	<u>00000004</u>	<u>00008004</u>	<u>00000004</u>	<u>00002000</u>
<u>+0.99999E+00</u>				
<u>+0.32827E+00</u>				
<u>+0.19863E-01</u>				
<u>-0.92564E-01</u>				



The correlation coefficients are output in floating point form. The five digit decimal number to the right of the decimal point should be multiplied by  $10^E$  raised to the power of the number following the E (E is for exponent). The equation by which the correlation coefficient is reached is the following:

$$\text{Correlation coefficient to the } i\text{th point} = \frac{(\text{raw value of the } i\text{th point})}{(\text{raw value of the first point})}$$

In the above typeout example, the correlation coefficients can be interpreted as follows:

1st point / 1st point	=	+0.99999 E + 00
2nd point / 1st point	=	+0.32827 E + 00
3rd point / 1st point	=	+0.19863 E + 00

AGAIN, NOTE: The correlation coefficients obtained from this routine when cross-correlation is performed, bear no resemblance to the correct correlation coefficients. The routine is only valid for obtaining correlation coefficients from an autocorrelogram.

## MISCELLANEOUS

During data collection, checks for keyboard commands are made only during the display routine. In Normal Mode, this is not a hindrance, since the display runs as a foreground program, being interrupted only to do a sweep and take a sample. In Batch Mode, however, the display routine does not run as a foreground program. There is not time. The display routine checks the keyboard only 3 times during the process time. Therefore, if the sample process time is long, the time between displays is long, and it follows that the response time to keyboard commands is also long. For example, if one is taking samples at .1 milliseconds, for 512 points, the delay between displays will be noticeable, as will response to commands. Also, when the sampling time is large and many points are requested (i.e.,  $R=20.0 \text{ } \# \text{ pnts} = 512$ ), the display will be severely degraded.



## APPENDIX

Binary Output Format ..... A

Attachment of an Analog X-Y Plotter ..... B

Reference for Statistical Equations ..... C



## A. Binary Output Format

When the ↑ B command is given, a binary dump of the correlogram will proceed on either the high or low speed punch. The dump will start with leader/trailer punches (these are channel 8 punches). For a description of paper tape punching format, see Introduction to Programming, Vol. 1, 4-12.

After the first leader/trailer punches, the ID code will be punched in ASCII format. This will be followed by more leader/trailer. The core image is preceded by an address. This is signified by a 7 channel punch with the most significant 6 bits of the address on the same line followed by the least significant 6 bits on the next line. A core image follows the address.

The first locations to be dumped are the parameters of the correlogram that are necessary for proper display and accurate typeout. In order of their dumping, these parameters are: CLKCNT (minus the clock rate); WRDCNT (minus the number of points in the correlogram); ENDTMP (end the address of temporary buffer -1); ENDPRM (end address of permanent buffer-1); SWEEPH and SWEEPL (the high and low order words of the sweep count); NUMBER (number of points); BTCFLG (this = 0 for normal mode, -1 for batch mode); and FLAG (this = 0 for autocorrelation, -1 for cross-correlation).

After the display and typeout parameters are punched, the address of the correlogram is punched; followed by a core image of the correlogram. After all information has been punched, a checksum is punched.

A checksum is a means of checking the validity of read-in. It is a 12-bit word which represents the sum of all of the punches in the tape that are not leader/trailer or ASCII information. It is formed by adding every line of punched data (7 channels) to a 12-bit word. Overflows are ignored, and the resulting 12-bit sum is punched at the end of the data. This is followed by more leader/trailer code.

When the binary loader reads a binary formatted tape, it keeps a running 12-bit sum of all punches between the end of the leader code and the checksum (note: the checksum punches are not included in the checksum). If the result is non-zero, an error on read-in has occurred and the tape should be read in again.



## B. Attachment of an Analog X-Y Plotter

Plotting of a displayed waveform may be easily accomplished by the use of an analog plotter. Since the display is itself an analog device, the information carrying signal is available at the X and Y input connections of the scope. The plotter should have an analog range of 0 to 10 volts.

To attach the plotter to the scope, simply run 2 wires from the plotter to the scope inputs for each of the x and y connections and their respective grounds. The wires need not be shielded. Now, whatever voltage is available to the scope is also available to the plotter. To plot a waveform, one slow display cycle should be gone through.

**CAUTION:** While the display is running at its normal speed, the plotter should be disconnected or turned off because the pen will shake furiously attempting to follow the display.



C. The reference for the statistical equations is:

Bendat, Julius S. and Piersol, Allan G., Measurement and Analysis of Random Data, John Wiley & Sons, Inc., N. Y. 1967.